pH Sensor on AlGaN/GaN Heterostructure with High Al Mole Fraction

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Abstract

pH sensor on AlGaN/GaN heterostructure with high aluminum mole fraction of 35% was developed. Evaluation demonstrated that transistor-like current-voltage characteristics with good pinch-off performance was confirmed in phthalate, phosphate and tetraborate standard buffer solutions. Decreasing on drain current and positive shift on threshold voltage were found with the pH value increasing. Sensitivity of about 57.7 mV/pH was obtained.

Keywords

pH Sensor; Gallium Nitride; AlGaN/GaN Heterostructure

Introduction

Measurement of pH value is very important in many fields, such as chemistry, medicine, biology, pharmacy and agriculture. Glass electrodes are commonly used for pH measurement. The miniaturization, stability and sensitivity of the pH sensor have been improved by introducing Si ISFETs (ion-sensitive field-effect transistors) (Bergveld 2003). However, Si ISFETs have still limitations in practical applications especially in high-temperature operation due to the material limitations of silicon. Gallium nitride (GaN) is a suitable material for developing chemical sensor owing to its chemical stability, low toxicity, and thermal stability. AlGaN/GaN heterostructure field-effect transistors (HFETs) are being developed as highly-sensitive pH sensor because of the high saturation velocity and high sheet carrier concentration of the two-dimensional electron gas (2DEG) layer. In this structure, an open-gate region is formed without metal gate for liquid contact (Kokawa et al. 2006, Kang et al. 2007, Abidin 2011). It is also possible to develop pH sensor operating at high temperature. However, the sensing mechanism of the GaN pH sensor is still not so clear. The native oxides, such as aluminum oxide and gallium oxide on the surface, is considered as a possible mechanism responsible for the pH sensing (Steinhoff et al. 2003). Especially, aluminum oxide demonstrated higher sensitivity (Bergveld 2003). Here, we will report the development and evaluation of a pH sensor based on AlGaN/GaN heterostructure with high Al mole fraction.

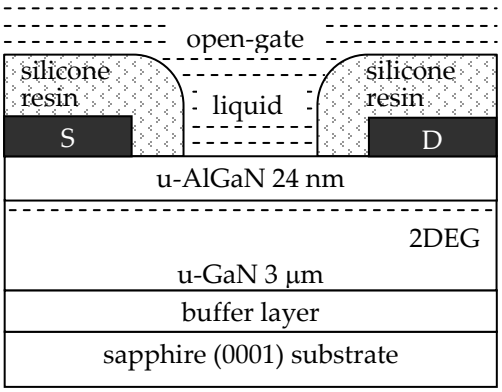

FIG. 1 THE CROSS SECTION OF THE PH SENSOR ON ALGAN/GAN HETEROSTRUCTURE

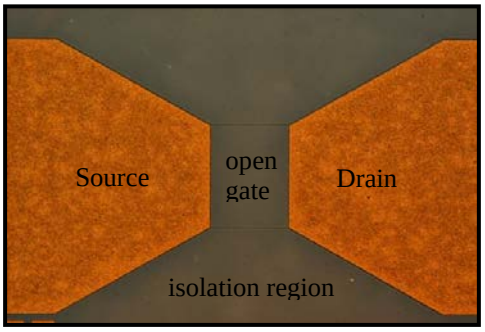

FIG. 2 THE TOP VIEW OF THE PH SENSOR ON ALGAN/GAN HETEROSTRUCTURE

Device Fabrication

The AlGaN/GaN heterostructure used in this experiment was grown on (0001) sapphire substrate,

which consists of a buffer layer, followed by a 3 μm undoped GaN layer (u-GaN), a 16 nm undoped AlGaN barrier layer (u-AlGaN) with Al mole fraction of 25% and a 8 nm undoped AlGaN barrier layer (u-AlGaN) with Al mole fraction of 35%. Device isolation was first done utilizing dry etching with etching depth of about 600 nm. Ohmic contact for drain (D) and source (S) was then formed using Ti/Al/Ti/Au (50/200 /40/40 nm) multilayer followed by annealing process with temperature of 850°C and period of 1 minute in N_2 ambient. Finally, the samples were diced into single chips and mounted on a teflon substrate by covering all the conducting area with silicone resin to avoid contact with solutions, leaving only a open-gate region to contact with the measured liquids. The open-gate area is with length of about 600 μm and width of 800 μm. The cross section and the top view of the pH sensor on AlGaN/GaN heterostructure is shown in Fig. 1, and Fig. 2, respectively.

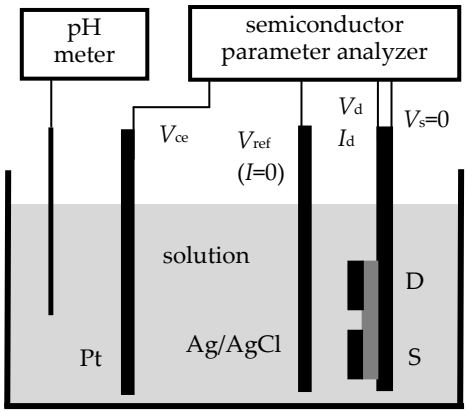

FIG. 3 THE MEASUREMENT SYSTEM OF THE PH SENSOR

Device Evaluation and Discussion

A semiconductor parameter analyzer (Agilent 4155C) was used to characterize the current-voltage characteristics at 23°C. An Ag/AgCl reference electrode was used to monitor the voltage in the liquid (V_{ref}). The liquid bias was applied to the solution via a platinum electrode (V_{ce}) or an Ag/AgCl reference electrode (V_{ref}). The drain current of the sensor was measured by applying a drain voltage. Three kinds of buffer solution, phthalate (pH=3.993), phosphate (pH=6.888) and tetraborate (pH=9.287) standard solution, were used to evaluate the pH sensor (Fig. 3) .

As shown in Fig. 4, transistor-like current-voltage characteristics was confirmed in all the liquids under different liquid bias (V_{ref}) applied via a Ag/AgCl reference electrode. Drain current decreased with the pH increasing. Fig. 5 shows the transfer characteristics of the sensor in the three kinds of liquid, where the liquid bias was applied via a Pt electrode and the voltage in the liquid was measured by an Ag/AgCl reference electrode (V_{ref}) under drain voltage of 0.1 V. Positive shift on threshold voltage can be found with the pH increasing. The threshold voltage shift is about 57.7 mV/pH estimated at the drain current level of 35 μA, as shown in Fig. 5. This is higher than that of a sample with aluminum mole fraction of 22%, where the average pH sensitivity is 52.2 mV/pH (Niigata 2014). It demonstrates that the sensitivity of the AlGaN/GaN pH sensor increases according to the Al aluminum mole fraction increasing.

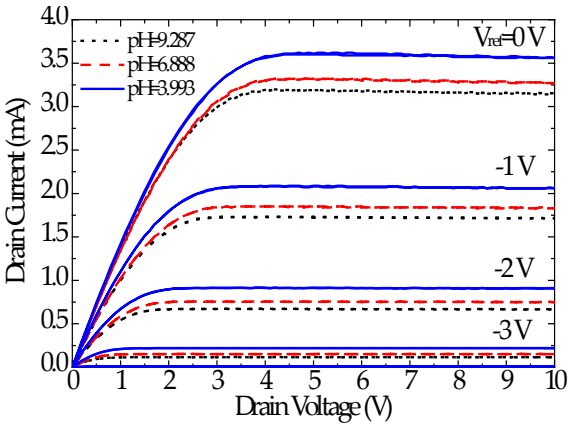

FIG. 4 CURRENT-VOLTAGE CHARACTERISTICS IN THREE KINDS OF LIQUID UNDER DIFFERENT LIQUID BIAS

The leakage currents measured from the platinum electrode in the three kinds of liquid are shown in Fig. 6. The leakage current in the platinum electrode is believed to be related with the electrochemical reaction in the open-gate region. However, as we can see in the figure, the leakage current is extremely low with current in nA order and also the pH-dependency does not appear in the three kinds of liquid.

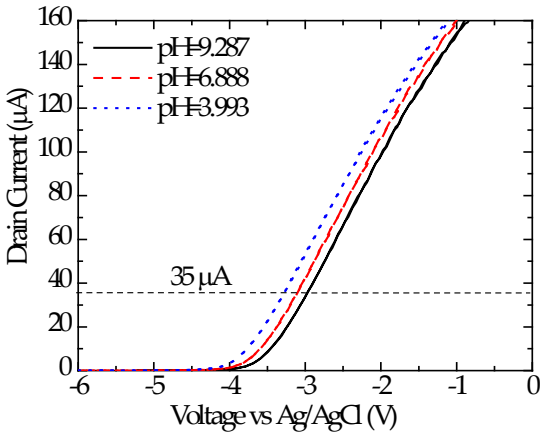

FIG. 5 THE TRANSFER CHARACTERISTICS OF THE SENSOR IN THREE KINDS OF LIQUID

Conclusions

pH sensor on AlGaN/GaN heterostructure with high

aluminum mole fraction of 35% was developed and evaluated. The operation of current-voltage characteristics was quite stable. Sensitivity of about 57.7 mV/pH was obtained which are close to the Nernstian response to H^+ ions. It demonstrated that high aluminum mole fraction contributed to the high sensitivity.

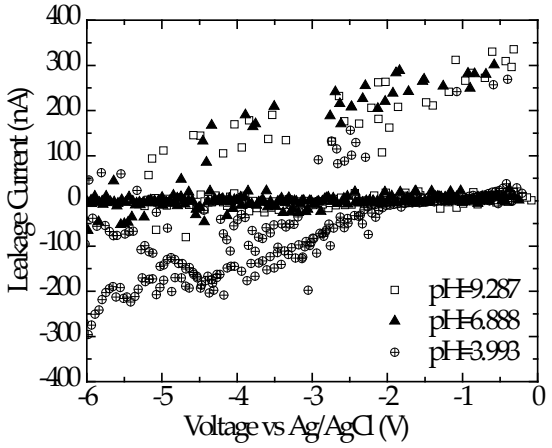

FIG. 6 THE LEAKAGE CURRENTS MEASURED FROM THE PLATINUM ELECTRODE IN THREE KINDS OF LIQUID

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